

Article

An Adaptive Control Method for the Distribution Valve of a Digital Pump

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Abstract: Perfect flow distribution is extremely important and essential for digital pumps. However, the fluctuation of motor speed and the change of valve dynamic characteristics cause the flow distribution flaw, which generates the backflow of the oil in the piston chamber and the decrease in pump volumetric efficiency. Based on the three-dimensional and mathematical modeling of the digital pump, the perfect distribution state of the digital pump is analyzed. Then, the adverse effects of the variations in motor speed and valve dynamic characteristics on the flow distribution of the digital pump were simulated and investigated by the software AMESim. To overcome the aforementioned problems, we proposed an adaptive control method for the flow distribution valve of a digital pump, which was realized by adopting the axis rotation angle and the pressure difference between the inlet and outlet of the flow distribution valve. The results show that the control signal of the flow distribution valve can be regulated automatically along with the motor speed and the valve dynamic characteristics, achieving the ideal flow distribution of the digital pump designed in this paper. The study can be used as a reference for the optimal design and prototype manufacturing of the digital pump.

Keywords: digital pump; flow distribution; adaptive control; high-speed on/off valve

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1. Introduction

Digital hydraulics technology has been rapidly developed and researched for applications in recent years. Its core is the discrete control of flow through the active and intelligent control of digital valves [1]. Digital hydraulic pumps adopt the above solution, and the chamber is independently controlled by using two digital valves. The chamber that is used is activated, and the ones not operated are banned. As a result, more intelligent control and less energy loss are realized [2]. However, the efficiency is affected by the response speed and the timing of the flow distribution valve (FDV). To further improve the operating characteristics and efficiency of the digital pump, improving the response times of the FDV is an effective and convenient manner.

With respect to the dynamic response of FDV, Zhao et al. investigated the effect of control current and voltage on the dynamic characteristics of FDV. Finite element analysis found that there was a balance between energy consumption and improvement of response speed [3,4]. Because the FDV is affected by different supply pressure, carrier frequencies, and coil temperatures, Su et al. proposed a dual voltage adaptive switching method, which can change adaptively according to the oil supply pressure and control port pressure [5]. Gao et al. put forward an adaptive PWM control method consisting of four PWM signals for FDV, the rising time of the pressure was reduced by 84.6%, and the temperature of the coil shell declined by 61.5 % [6]. Zhong et al. proposed a method for FDV which can adaptively select among multiple driving voltage sources when the oil supply pressure changes [7]. Zhong et al. also presented an FDV control method with adaptive switching

among five drive voltages, which reduced the open delay time by 66.7%, and lowered the close delay time by 87.5% [8]. Chapple et al. proposed a new type of poppet valve as FDV, and it is applied to high torque and low-speed systems to obtain higher efficiency and displacement control performance, but there are challenges with start-stop, valve timing, overpressure protection, and valve actuators [9]. The solenoid screw-in cartridge valves (SCV) are seen as having the potential to be applied to digital pumps. To improve the dynamic response of SCV and make it meet the flow distribution requirement of digital pumps. Yue et al. adopted positive and negative pulse voltage control for the solenoid coil, and the dynamic response characteristics are significantly enhanced by 56.67% compared to the conventional method [10]. Liu et al. proposed a new hybrid voltage control method consisting of preload voltage, positive pulse voltage, hold voltage, and negative pulse voltage, which reduced the open delay time by 74.24% and reduced the close delay time by 92.06% [11].

In the matter of flow distribution characteristics and control strategies for a digital pump, Pan et al. simulated the flow distribution characteristics of the FDV groups under clockwise and counterclockwise strokes of the motor, the steering variation process of the motor, and the effect of the switching valve frequency on the hydraulic motor [12]. Pederson et al. proposed continuous, discrete, hybrid dynamic approximate methods for digital pumps/motors, but there are still many challenges to be solved [13–16]. Based on the three pistons pump/motor, Breidi proposed a prediction for valve response delay time and mode switching algorithm using pressure fluctuations in high and low pressure lines, realizing an automatic selection of the most efficient control strategy among different displacement control strategies [17,18]. Nordas et al. detailed a simulation of the transient and steady-state response of digital displacement motors with full-stroke, partial-stroke, or sequential partial-stroke [19].

However, due to the changes in oil and coil temperature, the dynamic characteristics of the FDV can not always hold a constant in the operation of digital pumps [20,21]. In addition, the motor speed suffers from variations in the power grid. The above changes result in a flow distribution flaw in the digital pump, failing to achieve the expected flow distribution, which is manifested by fluid backflow and loss of volumetric efficiency during digital pump operation.

Therefore, an adaptive flow distribution control strategy of the digital pump is proposed to deal with the issue. The word “adaptive” refers to the ability of the proposed control method to maintain the perfect flow distribution of the FDV under the above variation. Firstly, we performed three-dimensional and mathematical modeling of the digital pump in Section 2. Secondly, in Sections 3 and 4, we analyzed the working characteristics of the digital pump with a perfect distribution and conducted a model-based simulation to investigate the impact of the changes in the motor speed and the dynamic characteristics of the FDV on a digital pump. Then, in Section 5, the principle of the proposed method is explained and verified. Finally, it was concluded that the adaptive control strategy could eliminate flow distribution error and keep the best efficiency, which not only improves the robustness and stability of the digital pump but also promotes the development of digital hydraulic technology.

2. Working Principle and Mathematical Model of the Digital Pump

2.1. Structure and Working Principles of the Digital Pump

A five-piston constant-speed digital pump with auxiliary check valves is shown in Figure 1. The motor converts electrical energy into mechanical energy, which drives the pump shaft and the eccentric cam to rotate. The piston is forced by the eccentric cam to make a sinusoidal motion and achieve fluid output. When the eccentric cam rotates from 0° to 360° , the piston moves from the top dead center (TDC) to the bottom dead center (BDC) and then returns to the initial TDC position; thus, the volume of the piston chamber completes a continuous variation. The piston and eccentric cam do not detach due to the return spring. When the piston moves from TDC to BDC, the piston chamber volume

becomes larger, and the pump enters the suction stage, the FDV, known as the high-speed on/off valve, is actively open. If there is an insufficient oil suction, oil replenishment can be completed through the auxiliary check valve. When the piston moves from BDC to TDC, the volume becomes smaller, and the pump switches to the pumping stage in which the high-pressure valve (HPV) is passively open.

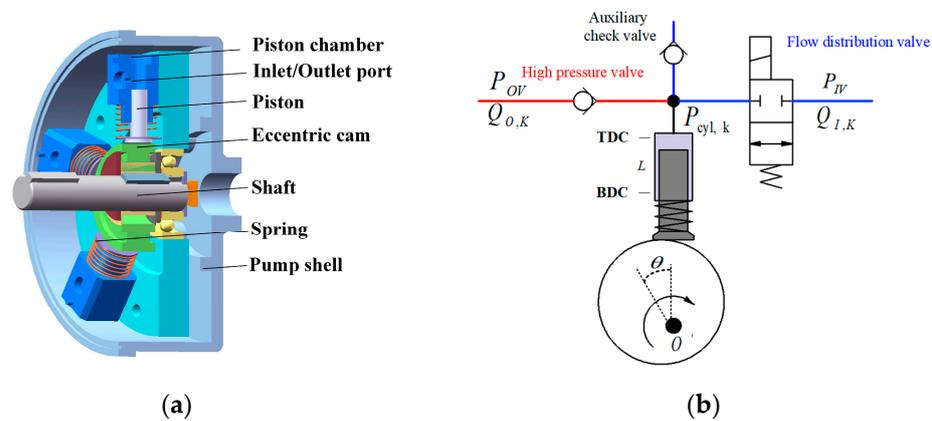


Figure 1. Structure and working principle: (a) Structural section drawing; (b) flow distribution principle.

2.2. Mathematical Modeling

The overall structure of the digital pump is divided into two parts, one is the flow distribution valve part, and the other is the piston part. The mathematical modeling of the two parts is as follows.

2.2.1. Force Balance and Response Characteristics of the FDV

The force balance of the spool of the FDV can be expressed as:

$$m\ddot{x}_s = F_e - F_{ss} - F_f - F_{ff} \tag{1}$$

On expression, m represents the total quality of the spool and the armature. X_s is the displacement of the spool, F_e depicts the electromagnetic force of the electromagnetic coil, F_{ss} is spring compression force, F_f demonstrates the total friction force of the spool and the armature, and F_{ff} is the flow force of the spool. Among them, the spring force acting on the spool can be expressed as:

$$F_{ss} = K(x_0 + x_s) \tag{2}$$

In the above expression, K represents the stiffness coefficient of the spring, and x_0 represents the initial compression displacement of the spring. The flow force acting F_{ff} can be divided into steady-state flow force and transient flow force. Steady-state flow force and transient flow force can be expressed as:

$$F_s = 2C_d C_v A_v \cos \alpha \Delta p \tag{3}$$

$$F_t = C_d w l \sqrt{2\rho \Delta p} \dot{x}_s \tag{4}$$

where F_s and F_t are the steady-state and transient hydraulic forces of the spool; C_d and C_v represent the flow coefficient and velocity coefficient of the valve port, respectively; A_v is the flow area of the valve; α and Δp represent the conical spool jet angle and the pressure difference between the inlet and outlet of the valve; w is the area gradient; l is the damping length; and ρ is the density of the oil.

For the convenience of modeling, this paper reduces the transient response of the FDV to a first-order inertia part and a delay part.

The time-domain response expression of the first-order inertial part is:

$$h_{FDV} = 1 - e^{\frac{1}{T} \cdot \tau_{FDV}} \quad (5)$$

where τ_{FDV} is the on/off valve time constant, h_{FDV} is the spool displacement.

2.2.2. Piston Motion Characteristics

Because the five pistons are identical, all five pistons can be described by modeling a single piston. The displacement of the piston is as follows:

$$x = \frac{L}{2}(1 - \cos \theta) \quad (6)$$

where L is the effective length of plunger. The relationship between angular displacement and angular velocity of the shaft is as follows:

$$\theta = \omega t \quad (7)$$

In Equation (7), ω is the angular velocity of pump shaft rotation. By substituting Equation (7) into Equation (6), we can obtain the following:

$$x = \frac{L}{2}(1 - \cos(\omega t)) \quad (8)$$

By differentiating Equation (9), the piston velocity equation is achieved as follows:

$$\dot{x} = \frac{L}{2}\omega \sin(\omega t) \quad (9)$$

The variation in pressure in the piston chamber is as follows:

$$\frac{dP}{dt} = \frac{\beta}{V} \left(q_H - q_L - \frac{dV}{dt} \right) \quad (10)$$

where P is the pressure in the piston chamber, β is the elastic modulus of oil, V is the volume in the piston chamber, q_H is the flow out through HPV, and q_L is the flow through the FDV.

2.2.3. Piston Volume Variation Characteristics

With no consideration of the plunger volume leakage, the change in the volume of the plunger chamber can be expressed as:

$$V = V_0 + \frac{x}{2}(1 - \cos \omega t) \quad (11)$$

where V_0 is the volume of the piston at the initial moment. The derivative of the piston volume is:

$$\frac{dV}{dt} = \frac{x}{2}\omega \sin \omega t \quad (12)$$

Instantaneous angle of piston:

$$\theta_k = \theta_0 + \frac{2 \cdot \pi}{n_{cyl}} \quad k \in (1, 2, \dots, n_{cyl}) \quad (13)$$

Flow through the inlet and outlet of the single FDV:

$$Q_{FDV, k} = C_d A \frac{\sqrt{2 \cdot \Delta P}}{\rho} \quad (14)$$

The total flow of FDVs:

$$Q_{in} = \sum_{k=1}^{n_{cyl}} Q_{FDV,k} \quad (15)$$

3. The Perfect Flow Distribution on Digital Pumps

The displacement of the digital pump is permitted to be controlled by different control strategies, and the most common and simple operation is the full-stroke control strategy (FSCS) that is adopted in this paper. In the whole pumping stage, the HPV is passively opening, and the FDV is actively closing. The oil in the piston chamber is compressed into the high-pressure circuit. In the entire suction stage, the FDV is actively opening, and the HPV is passively closing so that the digital pump sucks oil from the tank. Another type of control is the partial stroke control strategy (PSCS). Compared to FSCS, the active control of the FDV in the PSCS is strengthened. Whether the PSCS or FSCS of the digital pump, they both achieve the flow distribution depending on the precise opening and closing of the FDV; consequently, the perfect flow distribution of the digital pump has to consider the dynamic response of the FDV. The dynamic response of the opening and closing process of the FDV is shown in Figure 2. When the FDV receives the opening/closing control signal, the FDV goes through the opening/closing delay stage/ T_d and the spool opening/closing moving stage/ T_m until the response of the FDV is finished.

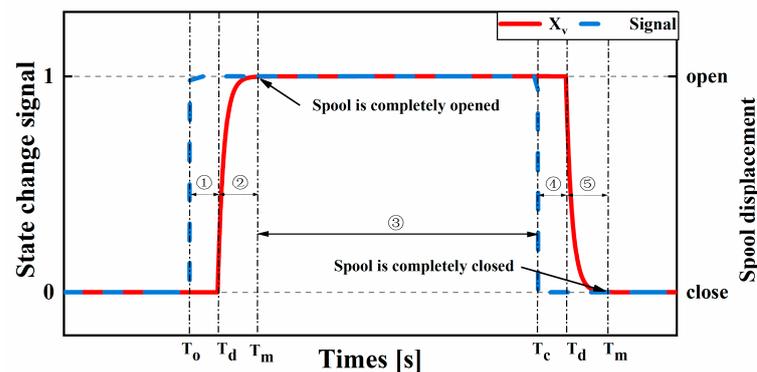


Figure 2. FDV dynamics response characteristic: ①: the spool opening delay stage; ②: the spool opening moving stage; ③: holding opening stage; ④: the spool closing delay stage; ⑤: the spool closing moving stage.

The operating characteristic curve of the digital pump at the perfect flow distribution condition is shown in Figure 3. It can be seen from plot 3 that the signal to open the FDV is made at this point, which is T_{oc} behind the TDC. The decision to close it is made at the moment where T_{cc} is ahead of the BDC. The T_{oc} is added to decompress the piston chamber in advance and make the pressure difference of the FDV equal to zero, which avoids the flow backward of the oil in the piston chamber. The value of T_{oc} is subject to the decompression time of the piston chamber and the spool opening delay stage of the FDV. The T_{cc} is created to ensure that the FDV has been closed completely when the piston reaches the BDC. The settings of T_{oc} must be decided by the sum of the closing delay stage and closing moving stage of the spool. Hence, it is obvious that the T_{oc} and T_{cc} is vital to the perfect flow distribution of the digital pump. From the flow curves of FDV shown in plot 4, it can be seen that the backflow does not occur with the appropriate T_{oc} and T_{cc} that brings the digital pump to the perfect flow distribution.

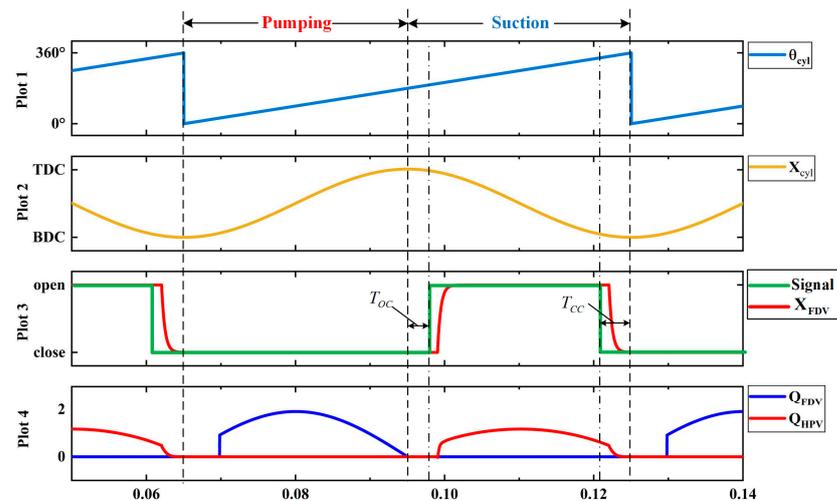


Figure 3. Perfect flow distribution state: plot 1: rotational angle; plot 2: Piston displacement; plot 3: The spool position and control signal; plot 4: FDV and HPV flow rate.

4. Simulation Modeling and Investigation

4.1. Digital Pump Simulation Model

According to the structure and working principle of the digital pump, it can be seen that the modeling of the digital pump involves multidisciplinary, such as mechanics, hydraulic transmission, electrical control, etc.; therefore, the multi-physics coupling modeling and analysis software AMESim is selected as tools to make study convenient.

As shown in Figure 4, the digital pump model with one piston is mainly composed of the hydraulic pump module and the control signal module. The control signal module is composed of the switch control signal module (SC_4) (SC_1) and the FDV adaptive signal module (SC_2). The main parameters of the model have been listed in Table 1. During the investigation of the flow distribution error stage, the adaptive signal control module is not involved in the control work. The correctness of the simulation model is verified by comparing the output flow of FDV and HPV, the backflow in simulation, and experiment results from the literature [14,16,17,22].

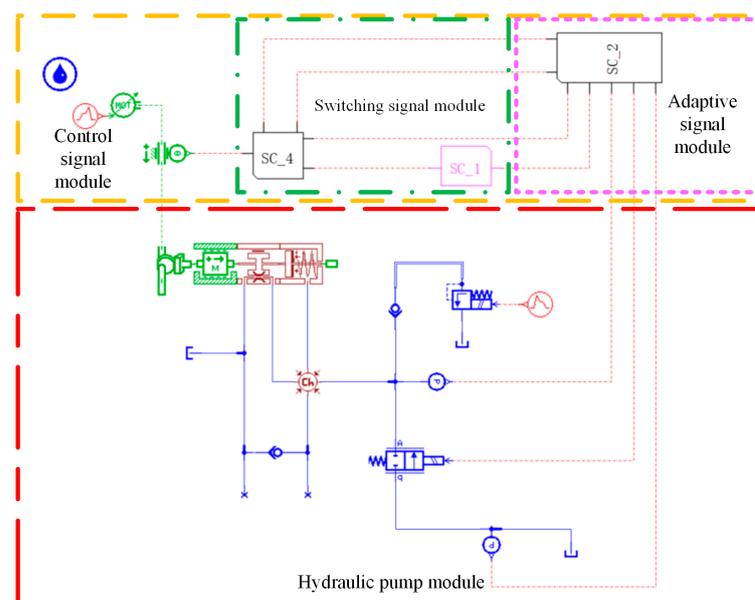


Figure 4. Simulation model of the digital pump.

Table 1. Main performance parameters.

Parameter	Value	Unit
Pump angular speed	1000	rpm
The radius of the eccentric	31	mm
Piston diameter	10	mm
Eccentricity	3.8	mm
Flow coefficient	0.7	
Dead volume of piston	0.08	mm ³
Chamber length	25.1	mm
FDV dynamic response	5	ms
T_{oc}	2	ms
T_{cc}	5	ms

4.2. Effects of Flow Distribution Error on Digital Pumps

The fluctuation of motor speed and the change in the dynamic characteristics of the FDV both make the FDV open and close at an inappropriate time; in other words, the FDV is activated too early or too late. To facilitate the analysis of the effect of incorrect FDV control on the digital pump, the T_{oc} is selected as -4 , -2 , 0 , 2 , and 4 ms, and the T_{cc} is -2 , -1 , 0 , 1 , and 2 ms. The greater the T_{oc} is, the later the FDV opens. The maximum T_{cc} means that the FDV first begins to close.

4.2.1. Effects of the T_{oc} on the Digital Pump

Figure 5 shows the main performance curves of the digital pump with T_{oc} increasing. From picture (a), as the T_{oc} increases, the opening time of the FDV spool is transferred from the pumping stage to the suction stage. When T_{oc} is -2 ms, the spool starts moving just at the TDC. It can be seen from picture (b) that the pressure of the piston chamber will fall to zero during at pumping stage with -4 ms, which reduces the output flow of the digital pump. On the contrary, when T_{oc} is equal to 4 ms, the pressure of the piston chamber becomes negative because of the late opening of the FDV. According to the picture (c) and (d), the backflow amplitude gradually becomes smaller with the increase in the T_{oc} . When T_{oc} is greater than 2 ms, no backflow occurs. It can also be apparent that oversized T_{oc} forces the FDV to open too late, which results in the sucking oil having to be executed by the auxiliary check valve.

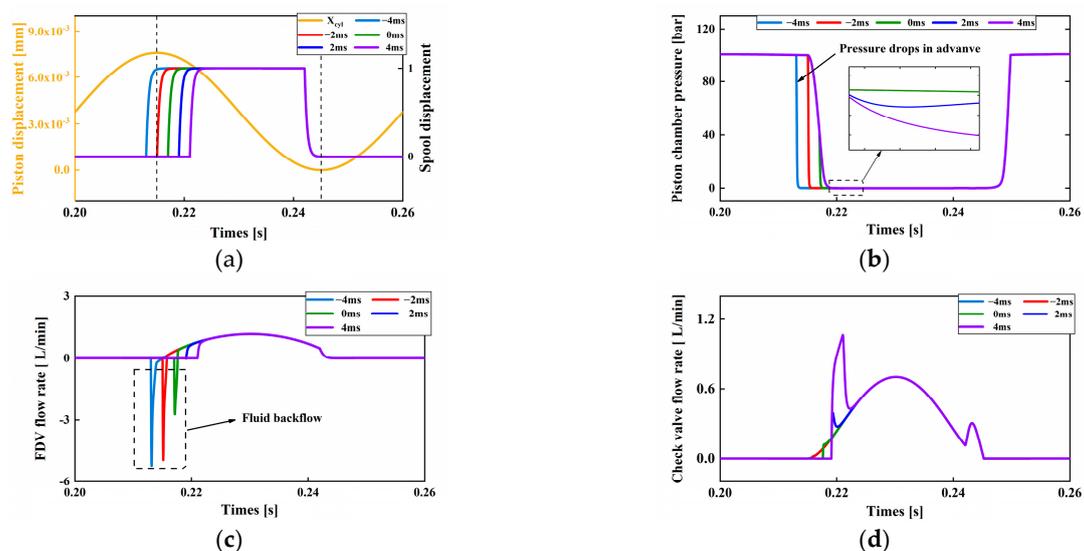


Figure 5. Characteristics with different T_{oc} : (a) spool displacement; (b) piston chamber pressure; (c) FDV flow rate; (d) auxiliary check valve flow rate.

4.2.2. Effects of the T_{cc} on the FDV

As shown in Figure 6a, the FDV began to close at different piston displacements with various T_{cc} . When T_{cc} is set to 2 ms, the FDV has been closed before the piston travels to the BDC. It can be found from pictures (c) and (d) that the FDV flow descends to zero at the last of the suction stage, and the flow through the auxiliary check valve is the highest correspondingly. Picture (b) shows that there is a sudden pressure reduction in the piston chamber due to the too-early closing of the FDV. The reason for this appearance is that the pressure difference with only the auxiliary check valve working is greater than the one of the simultaneous operation of the two valves. Moreover, we can see that the pressure rise of the piston chamber with T_{cc} being -2 ms lags behind the other. The pressure variation in the piston chamber is identical except for -2 ms because the auxiliary check valve can compensate for the shutting off of the FDV.

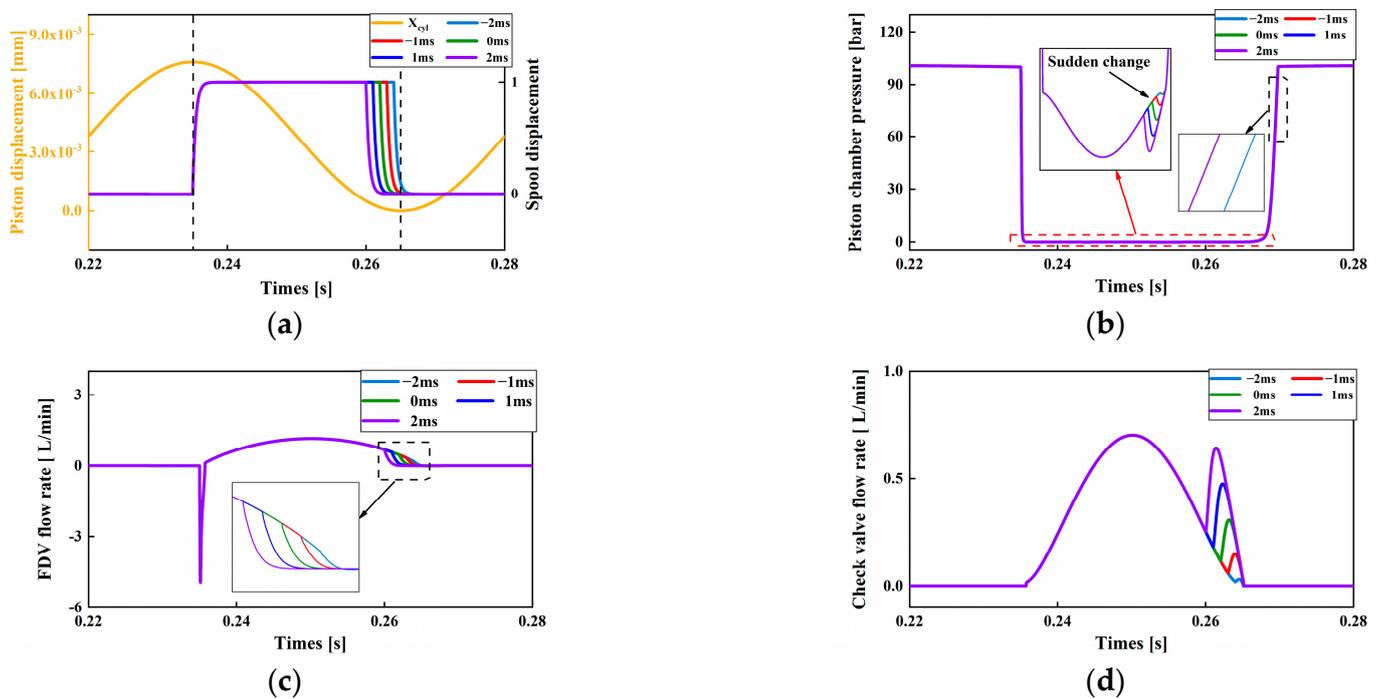


Figure 6. Characteristics with different T_{cc} : (a) spool displacement; (b) piston chamber pressure; (c) FDV flow rate; (d) auxiliary check valve flow rate.

5. Adaptive Control of the FDV

5.1. Control Principle of Adaptive Control of the FDV

From the viewpoint of the producing mechanism of the backflow and the volumetric efficiency decrease, we propose an adaptive control method for the FDV of a digital pump, which detects the rotation angle of the digital pump shaft and the pressure difference between the inlet and outlet of the FDV. The flowchart of the adaptive control method is demonstrated in Figure 7.

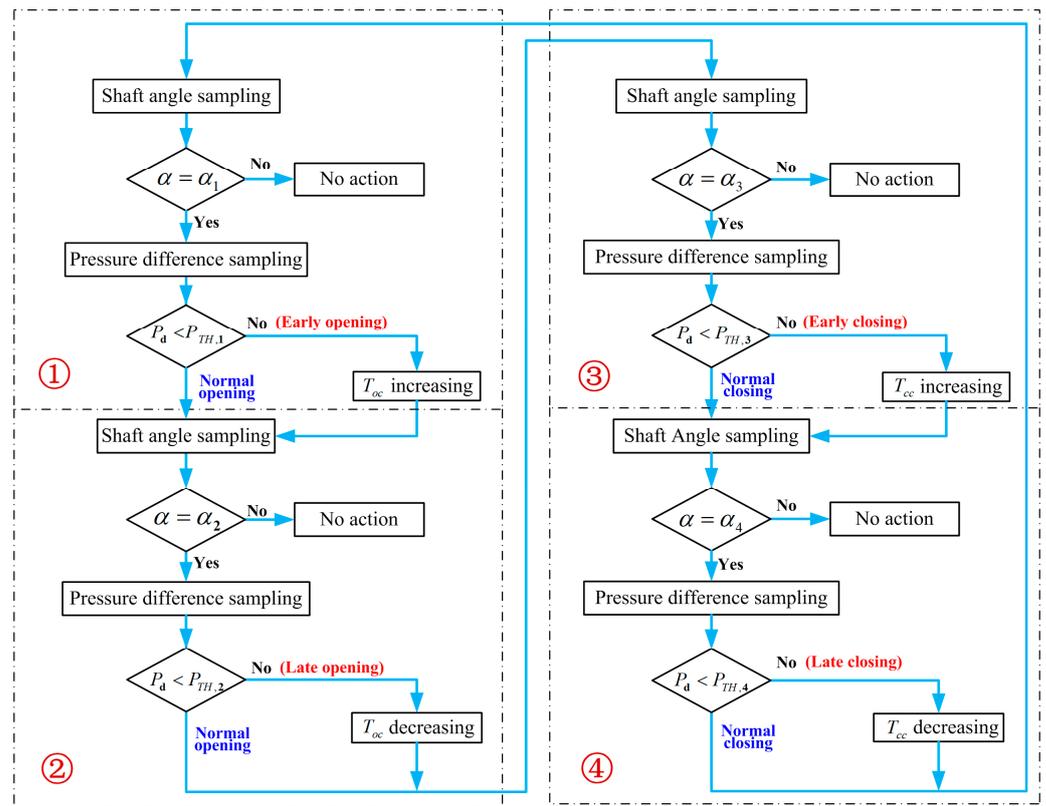


Figure 7. The flow chart for adaptive control of the FDV.

As can be seen from Figure 7, the whole adaptive control of the FDV is divided into four parts that are as follows: ① early opening handling module, ② late opening handling module, ③ early closing handling module, and ④ late closing handling module. These four modules are executed once in order when the pump shaft rotates by 360 degrees, which keeps the adaptive control operation of the FDV running and achieves the adaptive adjustment of the T_{oc} and T_{cc} . The adaptive control of the FDV has four important shaft angles α_1 , α_2 , α_3 , and α_4 , at which the early opening, late opening, early closing, and late closing are inspected, respectively. The locations of these four critical angles are represented in Figure 8.

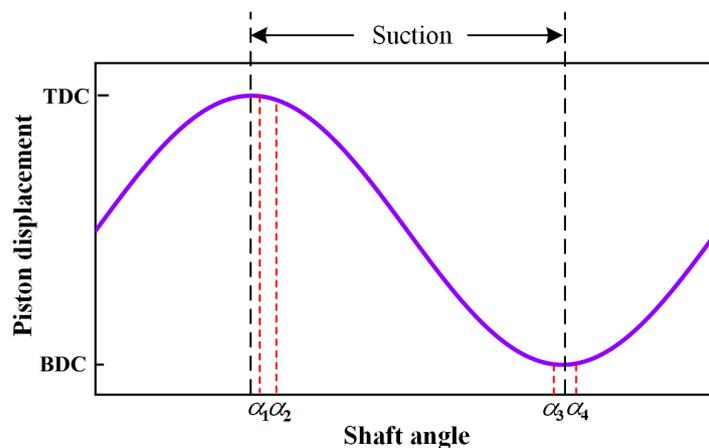


Figure 8. The diagram of the inspection angles of flow distribution.

The detailed control strategy of adaptive control of the FDV is described as follows.

1. In the early opening handling module, when the shaft angle collected by the rotary encoder is not equal to the early opening assessment angle α_1 . Nothing special has to be performed. Conversely, the pressure difference between the inlet and outlet of the FDV is sampled and compared with the set threshold $P_{TH,1}$. If the pressure difference is greater than the threshold, the FDV is opening too early and the T_{oc} is raised. According to Figure 5b, when the FDV is opening in advance, the pressure of the piston chamber is not as great as expected because the high-pressure oil in the piston chamber will be discharged through the FDV; on the contrary, the control of the FDV is normal, and the next module is subsequently called.
2. When the shaft of the digital pump is late opening assessment angle α_2 , the late opening of the FDV is detected and treated. If the FDV is not activated at α_2 , the oil enters the piston chamber only via the auxiliary check valve, and the pressure difference of the FDV is smaller than the one of the two valves opening. The pressure difference comparison of the FDV closing and the two valves opening is displayed in Figure 9. If the late opening of the FDV is perceived, the decrease in T_{oc} is implemented.
3. The operating principle of adaptive control of the FDV early closing is similar to the late opening; the T_{cc} decreases when the FDV is prematurely deactivated. The comparison between P_d and $P_{TH,3}$ and T_{cc} adjustment are both carried out with the shaft angle equaling to α_3 .
4. The solution to the late closing of the FDV is entirely consistent with the early opening handling module. If the FDV is not closed in time, the piston chamber is connected to the tank, and the pressure of the piston chamber can not rise to the threshold $P_{TH,4}$ at the shaft angle α_4 . In this case, the T_{cc} is gradually increased to the early opening of the FDV.

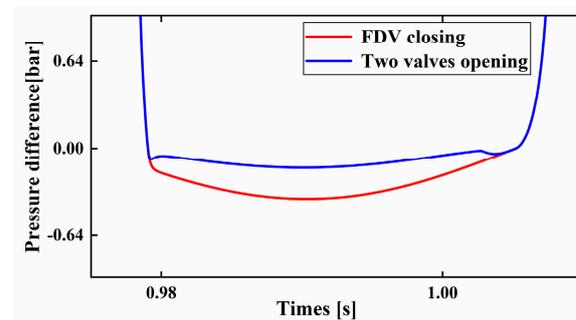


Figure 9. Pressure difference comparison of FDV closing and two valves opening.

5.2. Simulation Analysis of Adaptive Control of the FDV

5.2.1. The Results with Motor Speed Changes

The step changes in motor speed are used to analyze and verify the effectiveness of the adaptive control method proposed in this paper. The flow rate of the FDV is shown in Figure 10a with motor speed fluctuations. It can be seen that the flow rate of the FDV is proportional to the motor speed, but the backflow of the FDV emerges after the motor speed variation. This phenomenon is weak when the motor speed step increases but stronger when the speed step decreases. The increase in motor speed means that the activation and inactivation of the FDV are performed; hence, there is a small amount of backflow at the moment of the FDV closing after 2 s. From pictures (b), (c), and (d), the T_{oc} and T_{cc} are automatically elevated from -12 to -6 and from -22 to -32 under adaptive control and kept in the optimum values related to the motor speed.

When the motor speed reduces by 500 r/min at 4 and 6 ms, a violent flow backward appears in the opening process of the FDV. In the timeline, the moment of action of the FDV does not change, but the movement of the plunger was delayed. It is obvious that the sudden reduction in the motor speed is equivalent to the early opening and closing of the FDV. According to the module 1 and 3 in Figure 7, the T_{oc} and T_{cc} should be diminished with the premature motion of the FDV, which can be proved by the curves reducing from

−6 to −16 and from −32 to −21 between 4 and 8 ms in Figure 10b,c. Additionally, it can be seen from Figure 10d that this method can improve the situation of excessive pressure difference during FDV action. As a result, the adaptive control approach is better able to cope with the motor speed change, and the backflow phenomenon is eliminated.

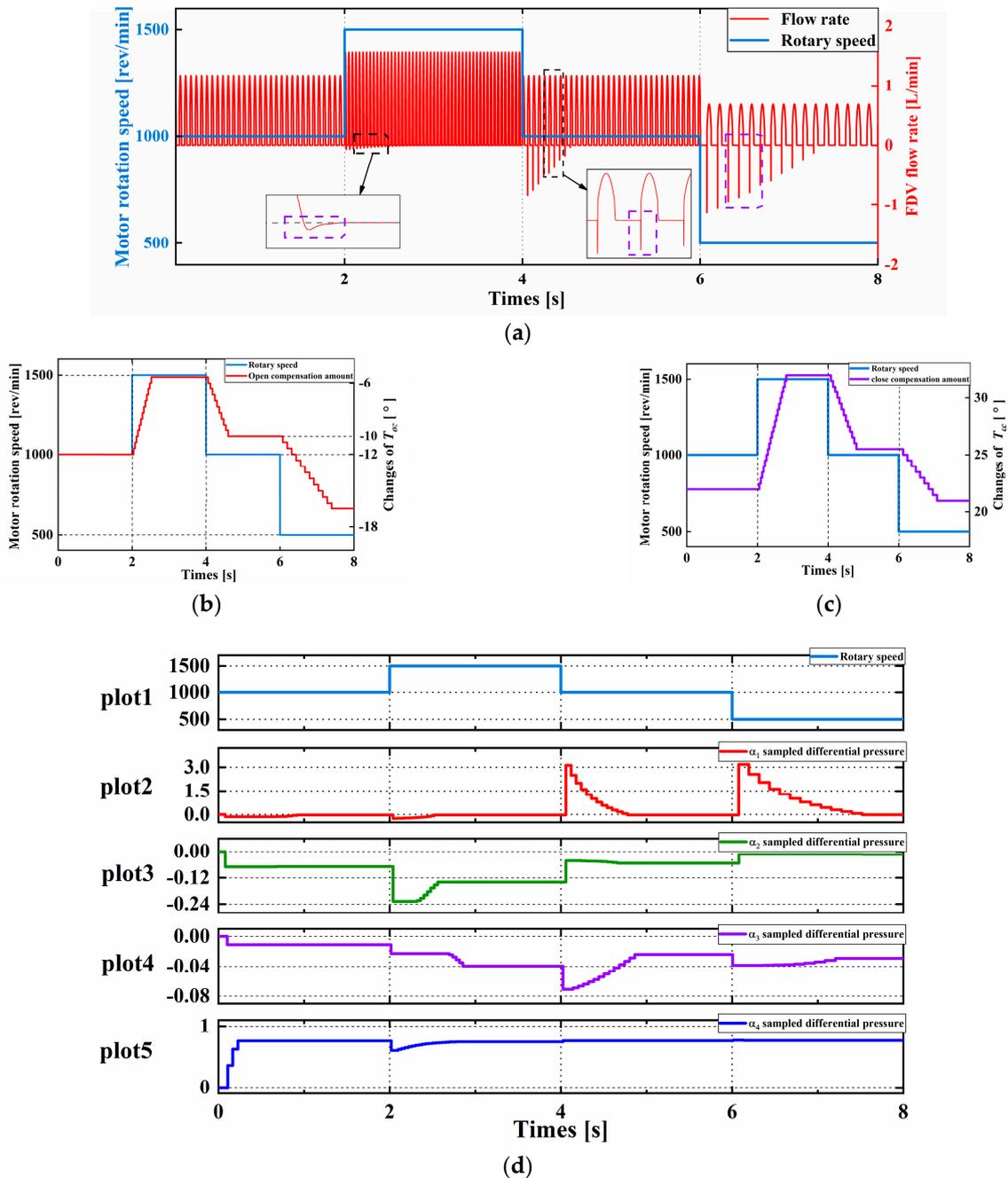


Figure 10. The results with different motor speeds: (a) flow rate of FDV; (b) T_{oc} curve; (c) T_{cc} curve; (d) plot 1: Motor speed; plot 2–4: differential pressure at $\alpha_1, \alpha_2, \alpha_3, \alpha_4$.

5.2.2. The Results with the Different Dynamic Responses of the FDV

It is found from Figure 2 that the dynamic response of the FDV contains the delay and spool moving two parts. In this paper, the spool moving time of the FDV is altered to ascertain the availability of the adaptive control, the motor speed is set to 1000 rpm, and the delay time of the FDV is still held at the primitive value 2 ms. As shown in Figure 11a, the time spent by the spool moving varies from 1 ms to 9 ms. The initial phase is set so

that the FDV is already in a perfect flow distribution when the spool starts moving in the opening stage. The time the spool starts to open and close has no change because the delay time and control signal of the FDV is invariant, which prevents the early or late opening of the FDV from happening. Hence, the value of T_{oc} shown in Figure 11e is equivalent. The longer spool moving time may cause the complete closing of the FDV at the pumping stage of the digital pump, making more backflow, which can be observed in Figure 11b. Figure 11c shows the flow of the FDV closing process utilizing the adaptive control, and the backflow is completely removed. The backflow contrast curves of the FDV before and after optimization are unlocked in Figure 11d. When the closing moving time of the FDV is greater than 3 ms, the late closing trouble takes place and is solved by means of increasing T_{cc} , which can be confirmed by the increase, respectively, from 22 to 29, 38, and 42 in Figure 11f.

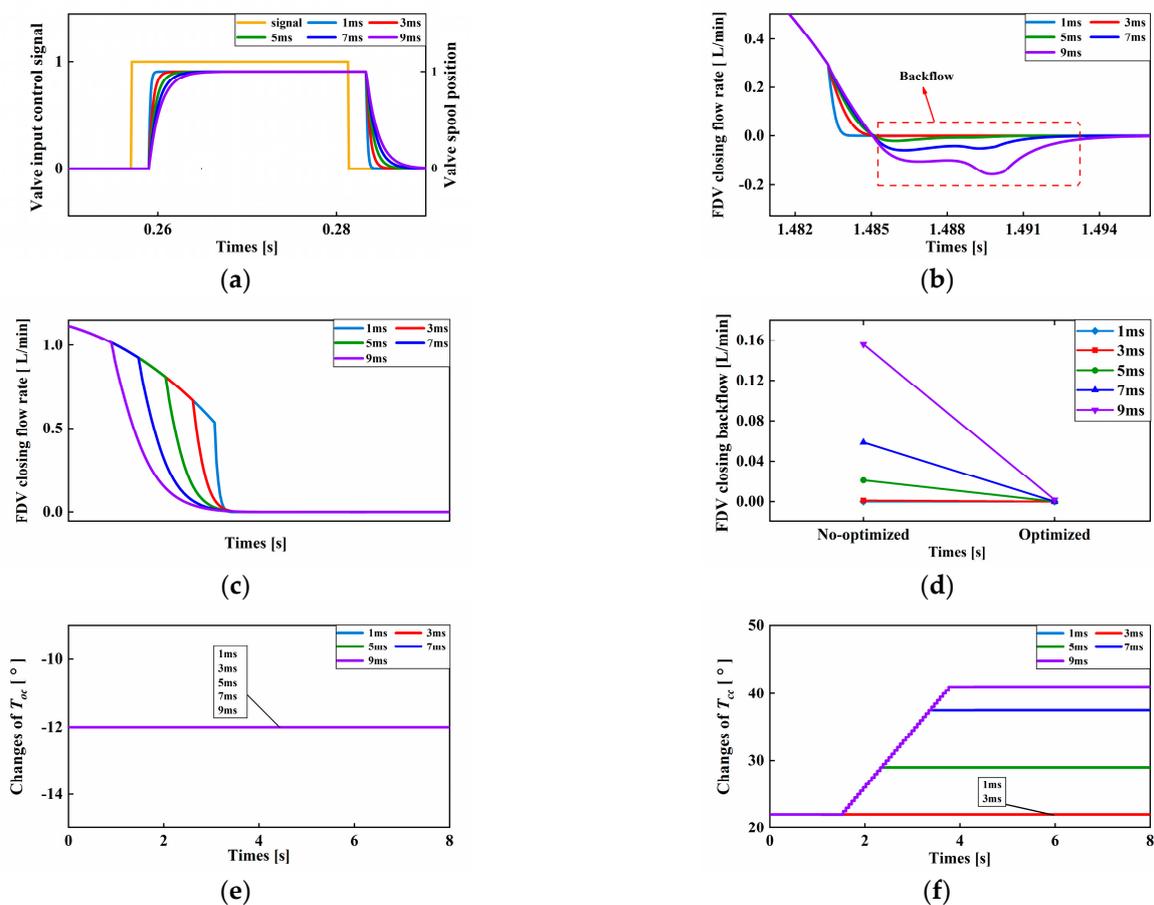


Figure 11. The results of different dynamic characteristics of FDV: (a) spool displacement; (b) flow rate before optimization; (c) optimized flow rate; (d) comparison backflow of FDV closing process; (e) T_{oc} curve; (f) T_{cc} curve.

6. Conclusions

In this paper, the self-adaption flow distribution of the digital pump with FDV and an auxiliary check valve is studied. Inappropriate control signal T_{oc} and T_{cc} generated by the changes in the FDV dynamic properties and motor speed will bring the early or late working of the FDV and lead to the backflow of oil in the piston chamber and more volumetric efficiency losses. As a consequence, T_{oc} and T_{cc} of the FDV must be corrected in real-time to avoid flow distribution errors.

A new adaptive control method for the FDV is proposed to automatically adjust the T_{oc} and T_{cc} and compensate for the inevitable undulation of the motor speed and the variation in FDV response. The approach suggested is completed by conducting four

compares between the pressure difference sampled at the shaft angle $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ with the pre-set thresholds.

The simulation results reveal that when the adaptive control is implemented, the T_{oc} and T_{cc} can be autonomously revised with the aforementioned changes, and the undesired backflow is cleaned up. The work in the future is the test rig development of the digital pump by utilizing the semi-physical simulation system in our laboratory and validating the availability of this solution through the experiment.

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